Higgs production at Hadron colliders as a probe of new physics

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The coupling of the Higgs with gauge bosons g_{hVV} ($V = g, \gamma, W, Z$) can receive non-decoupling corrections due to heavy quanta. Deviations from the SM predictions are described by a set of parameters ϵ_V, which can be related to the parameters S, T for specific models. The Higgs production by gluon fusion can be used to probe ϵ_g at Tevatron, whereas the promising Higgs decay into WW^* can probe ϵ_W. We find that the resulting bounds may imply the exclusion of heavy particles that receive their mass directly from the SM Higgs, including additional standard or mirror families, chiral colored sextets and octet quarks. Within the MSSM, we also find that gluon fusion is a sensitive probe for the spectrum of squarks masses.

1.- Introduction. The discovery of the Higgs boson as the remmant of the mechanism of electro-weak symmetry breaking (EWSB), is one of the most cherised goals of present and future high-energy experiments. Within the minimal standard model (SM), the mass of the physical Higgs particle is a free-parameter, but present data seems to favor a moderate mass ($105 < m_h < 220$ GeV) [1], however this conclusion may be changed by the presence of new phyics with an scale $\Lambda \simeq O(1)$ TeV [2]. On the other hand, the minimal supersymmetric version of the SM (MSSM), which is one of its most appealing extensions, predicts a light Higgs boson, with an upper mass bound of about 130 GeV [3]. Detection of the full spectrum of Higgs bosons in the SM and beyond, has been extensively studied, because it constitutes an important test of the possible realization of the Higgs mechanism in fundamental physics.

The characteristic Higgs boson couplings determine the strategies employed for its search at present and future colliders. For instance, at LEP the large couplings of the Higgs with massive gauge bosons allows to use the reaction $e^+e^- \to Z + h$; whereas at next linear colliders (NLC) it will also be possible to study Higgs production by WW and ZZ fusion. On the other hand, Hadron colliders can also test these couplings, either through the reactions $pp \to W + h, Z + h$, or through the decays $h \to WW, ZZ$; vector fusion can also be used for heavy Higgs masses. The couplings of the Higgs with the heavier fermions, can be studied either by open production of $t\bar{t}h, b\bar{b}h$ or by the loop-induced coupling with gluon and photon pairs ($hgg, h\gamma\gamma$) [4]. Any additional heavy particle that receive its mass from the SM Higgs mechanism, will couple to the Higgs with strength proportional to the particle mass itself, which means that such heavy quanta will induce non-decoupling contributions to the 1-loop vertices hgg, $h\gamma\gamma$. Moreover, since these effects will compete at the same order with the SM loop, it can be a significan effect that may be probed at future colliders, as has been explored in previous studies [5]. However there is another important effect not considered previously, namely that the presence of these new particles could also induce non-decoupling corrections to the tree vertices hff, hWW and hZZ [6], which can affect the decay rate of detectable signatures, and thus must be included in the analysis.

In this papaer we study the effect of additional colored particles in the loop vertex hgg, and the bounds that could be obtained at Tevatron (RUN-II). We shall identify two cases, in the first (Scenario-I) we consider the situation when the mass of heavy colored particles comes from the SM Higgs boson, but which are weakly bounded by electroweak precision meassurements, i.e. we simply assume that there is some unspecified physics at the scale of the mass of the new particles that makes their contribution to the Peskin-Takeuchi parameters S, T to be within experimental range [12]. The second case (Scenario-II) will include a heavy fourth family, for which we find that the corrections induced by the heavy fermions on the vertices hgg and hWW/hZZ are correlated, and in fact can be written in terms of the parameter T. We also study gluon fusion for the MSSM higgs bosons, as a possible test for the mass spectrum of squarks. Large effects are obtained when the loop amplitude includes non-degenerate squark masses, which could be realized in many particular models [7]. These results suggest that the discovery of a Higgs boson can be turned into a new tool for high precision electroweak physics studies.

2.- Parametrization of new physics in Higgs couplings. In order to probe heavy scales through their effect on the Higgs coupling, we shall consider extensions of the SM that include additional particles, but with a minimal Higgs sector consisting of one doublet. We are interested in the possible representations that can receive their mass from the SM Higgs mechanism. Because of the quantum numbers of the SM Higgs, we are restricted to consider only fermion doublets and singlets. Then the possibilities reduce to: a) additional families with SM quantum numbers b) additional mirror families and c) a combination of the above. Within cases a and b, new quarks must have the same color properties as in the

SM, but since for case c it is possible to cancel anomalies among the quarks, they could lay in larger $SU(3)_c$ representations, like sextets or octets. Since these new states have electroweak charges, they will contribute in general to the parameters S,T,U, but not necessarily. Present global fits for electroweak data seem to exclude more than one additional SM family [8], however this conclusion relies on the assumption that no other physics occurs at the energy scale of the new fermion masses, which may not be the case in SUSY models. For instance, consider a model with a complete SUSY 4th family, in the limit $m_A >> m_Z$, under which the light Higgs boson h^0 behaves like the SM Higgs, and also assume a mass degeneracy for the components of the fermion doublets, as well as for the sfermions, this gives $T = 0$; whereas fermions give $S = 2N_c/6\pi$, the contribution of sfermions to S is given by $S = \frac{N_c}{36\pi} log(\frac{m^2_{\tilde{u}_{Li}}}{m^2_{\tilde{d}_{Li}}})$ [9], thus by choosing the appropriate masses one could decrease the total value of S, and satisfy present experimental constraints. This first scenario, where we have new particles that receive their mass from the SM Higgs mechanism, but are weakly constrained by electroweak precision data, is the right place where the study of the Higgs signal can test the presence of such heavy particles. For the second case, when the corrections to the different vertices hVV are correlated, one must include all the corrections to the relevant branching ratios for the analysis of bounds; here we can also obtain bounds on the heavy quanta, though they will be somewhat limited.

We shall describe the effects of heavy quanta on the higgs couplings to gauge bosons, by writing them as: $g_{hVV} = g^{SM}_{hVV}(1 + \epsilon_V)$, where $V = W, Z, g, \gamma$, and similarly for the fermion couplings $g_{hff} = g^{SM}_{hff}(1 + \epsilon_f)$. The parameters $\epsilon_{f,V}$, encompass the effects of heavy quanta. In general, the expression for $\epsilon_{g,\gamma}$ will be give by a ratio of complicated loop expresions, however since we are interested in the limit $m_h << M_{heavy}$, one can use the low-energy theorems [10], to relate $\epsilon_{g,\gamma}$ to the beta-function coefficients for the corresponding coupling constant $(\beta_{I,X})$. Thus, the higgs-gluon coupling is given by $\epsilon_g = \beta_{3,X}/\beta_{3,t}$, where $\beta_{3,t(X)}$ denote the contribution of top and heavy quanta to strong beta function. The values of ϵ_g arising from a pair of heavy color triplets, sextets and octet quarks are : ϵ_g = 2, 5 and 6, respectively, whereas a new SM family plus its mirror partner gives $\epsilon_g = 4$. It is remarkable that coming stages of Tevatron will be able to test these values at significant levels.

The correction induced by the heavy quanta on the couplings hWW, hZZ can also be derived using the low-energy theorems. However, for the case of a fourth heavy family, one finds an interesting relation between $\epsilon_{f,W,Z}$ and the corresponding expression for the parameter T, namely,

$$\begin{aligned}\epsilon_f &= \frac{\alpha T}{2} + \frac{N_c G_F}{12\sqrt{2}\pi^2}(m_1^2 + m_2^2)\\ \epsilon_Z &= -\frac{N_c G_F}{6\sqrt{2}\pi^2}(m_1^2 + m_2^2)\\ \epsilon_W &= \epsilon_Z + \frac{\alpha T}{2}\end{aligned} \quad (1)$$

where T includes the contribution of the fourth family fermions with masses $m_{1,2}$.

We could also consider effects arising from heavy particles that receive their mass from the breaking of new symmetries characterized by a large scale $V_{new} >> v = 246$ GeV, induced by another set of heavy Higgs bosons (Φ_{new}). Suppose this is communicated to the SM Higgs by including in the scalar potential a mixing term of the form: $\lambda|\Phi_{new}|^2|\phi_{sm}|^2$. Then one can also include the contribution of these ultra-heavy particles to the parameters ϵ_V. However, we found that in this case the mixing angle that transforms the Higgs weak to mass-eigenstate basis, is suppressed by the large scale (V_{new}), and it induces decoupling effects at low-energies, namely $\epsilon_g \simeq v/V_{new}$.

3.- The mechanism of gluon fusion and bounds on ϵ_g . The contribution coming from the new particles will modify the cross section for gluon fusion, as follows: $\sigma(pp \to h + X) = \sigma_{SM}(1 + \epsilon_g)^2$ where the SM cross-section σ_{SM} can be written in terms of the Higgs decay width $\Gamma(h_{SM} \to gg)$; details of the equations can be found in the literature [11], Since the new particles modify the decay width into $h \to gg$, it will enhance the production by gluon fusion reaction, but this enhancement could work against the final signal rate, which usually involves some decay of the Higgs boson into a mode with clear signature, like $h \to WW^*$ or $\gamma\gamma$ for the intermediate Higgs mass region. Both effects can be taken properly into account in the analysis by writing the product of the cross-section times the branching ratio of the signal as $[\sigma \times B.R.(h \to VV)]_{new} = R_V \times [\sigma \times B.R.(h \to VV)]_{SM}$, where R_V is given by ,

$$R_V = \frac{(1 + \epsilon_g)^2(1 + \epsilon_V)^2}{[1 + \sum_Y(\epsilon_Y^2 + 2\epsilon_Y) * B.R.(h_{SM} \to YY)]} \quad (2)$$

where the sum in the denominator runs over $Y = t, b, g, A, W, Z$.

We can obtain bounds on the parameters $\epsilon_{g,W}$ using gluon fusion and the decay $h \to WW^*$ at Tevatron, which was studied in detail in ref. [13], this work concluded that it is possible to detect a SM Higgs boson with an integrated luminosity of 30 fb^{-1}, provided that an optimized selection of cuts is implemented; here we shall only use their first stage of cuts, namely: transverse lepton momentum $p_t(e, \mu) > 10$ GeV, psedorapidity $\eta_{e,\mu} < 1.5$, lepton invariant mass $m_{ll} > 10$ GeV, jet resolution $\Delta R(l - j) > 0.4$, missing transverse energy $E_T > 10$ GeV. For the case when the corrections to ϵ_W can be neglected (Scenario-I), the above cuts already allow us to get interesting bounds on the parameter ϵ_g at

95 % c.l., as it is shown in figure 1 (for 2 and 10 fb^{-1}). These bounds will in turn constrain the presence of heavy colored particles coming from cases a, b and c, provided that the Higgs mass lays in the intermediate mass range. The interception of the exclusion lines with the straight dashed line (which corresponds to $\epsilon_g = 2$), shows the values of Higgs masses where it will be possible to limit the presence of a pair of heavy color triplets. Furthermore, since sextets and octet quarks give a larger value of ϵ_g, their presence could be excluded too.

However, these bounds need some clarfication for the case when the new physics also modifies the parameters $\epsilon_{W,Z}$, since this will affect the decay rates into $h \to WW^*$. For the fourth family case (Scenario-II), the corrections to the vertex hVV are negative (as compared with the positive tree-level value) and grow with the mass of the heavy quanta; for instance for fermion masses of order 500 (700) GeV the deviations from the SM tree-level couplings are of order - 27 (-52) % [6], which seems to imply that the signal will no longer be detectable i.e. one can only probe heavy but not ultraheavy quanta. With 10 fb^{-1} of integrated luminosity, it will be possible to exclude only a limited range of fermion masses, up to about 900 GeV at best, as it is shown in table 1. However since for these heavy masses one enters into the non-perturbative domain one can not draw a definite conclusion, unless it is found an scheme to treat the non-perturbative Higgs effects. On the other hand, the decay into photon pair can also be used to probe higgs couplings at LHC; but in this case the W-loop dominates the amplitude, and the contribution from addditional fermions has opposite sign, which will make it difficult to separate the effects, or even worst, may conspire to reduce the signal.

3.- Probing a Non-universal sfermion spectrum. The MSSM includes two Higgs doublets, and the Higgs spectrum consists of two neutral CP-even scalars h^0 and H^0, one CP-odd pseudoscalar A^0 and a charged pair $H^\pm$ [14]. The Higgs sector of the model is completely determined at tree level by fixing two parameters, conventionally chosen to be $\tan\beta$ and the pseudoscalar mass m_A. At loop levels, the radiative corrections, mainly from top and stop, modify the tree-level mass bound ($m_h < m_Z \cos 2\beta$), allowing to have $m_h^{max} \simeq 130$ GeV [3]. The corrections to Higgs couplings can also lead to modification of its production mechanisms at hadron colliders, as previously studied [15,16]. Although conventional wisdom states that the contribution of top/bottom quarks (squarks) dominate the amplitude for the gluon fusion, and squarks from first and second generations can be neglected, it should be mentioned that this result only holds within the minimal SUSY breaking scenarios, where it is typically assumed that sfermions are mass degenerate, as required to respect FCNC constraints [17]. However, mass non-degeneracy for sfermions within the same family but different isospin can be acceptable, since it will only be midly constrained by the parameter T. In fact, some non-degeneracy can arises even in the minimal SUSY-GUT, by imposing universal boundary conditions at the Planck scale, rather than the GUT scale. Other cases that require non-degeneracy are models with additional D-terms [7], and in Finite Grand Unification [18].

Thus, it is interesting to find some process that could test the sfermion mass spectrum. In this letter we consider the decay $h \to gg$ (which determines the gluon fusion mechanism) to probe the structure of soft-breaking masses predicted by models of SUSY breaking. The expression for the decay width of $h \to gg$ that includes a non-universal mass spectrum for squarks, can be written as,

$$\Gamma(h \to gg) = \frac{G_F \alpha_s^2 m_h^3}{4\sqrt{2}\pi} |G_h|^2 \tag{3}$$

where

$$G_{h^0} = G_{t,\tilde{t}} + G_{b,\tilde{b}} + G_{LR} + G_{UD} \tag{4}$$

For $h = h^0$, G_h is given by:

$$G_{t,\tilde{t}} = -\frac{m_t^2}{m_h^2}\frac{\cos\alpha}{\sin\beta}[f_1(\lambda_t) + f_3(\lambda_{\tilde{t}_L}) + f_3(\lambda_{\tilde{t}_R})] \tag{5}$$

$$G_{b,\tilde{b}} = \frac{m_b^2}{m_h^2}\frac{\sin\alpha}{\cos\beta}[f_1(\lambda_b) + f_3(\lambda_{\tilde{b}_L}) + f_3(\lambda_{\tilde{b}_R})] \tag{6}$$

$$\begin{aligned} G_{LR} = \frac{m_W^2 s_w^2}{m_h^2 c_W^2} \sin(\beta+\alpha)[Q_u(f_3(\lambda_{\tilde{u}_R}) - f_3(\lambda_{\tilde{u}_L}) \\ +Q_d(f_3(\lambda_{\tilde{d}_R}) - f_3(\lambda_{\tilde{d}_L})] \end{aligned} \tag{7}$$

$$G_{UD} = \frac{m_W^2}{2m_h^2 c_W^2} \sin(\beta+\alpha)\Sigma_{u,d}[f_3(\lambda_{\tilde{u}_L}) - f_3(\lambda_{\tilde{d}_L})] \tag{8}$$

The expression for $h = H^0$ are obtained by making the replacements $\cos\alpha \to -\sin\alpha$, $\sin\alpha \to -\cos\alpha$, $\sin(\alpha+\beta) \to -\cos(\alpha+\beta)$; the explicit form of $f_1(z), f_3(z)$ can be found in ref. [11]. The contribution proportional to the fermion masses are kept only for the stop and sbottom ($G_{t,\tilde{t}}, G_{b,\tilde{b}}$), whereas the remmaining SUSY-breaking effects are kept for all sfermions (G_{LR}, G_{UD}). To reduce the number of parameters, we choose our μ, A_t values in such a way that one can neglect L-R mixing, which was found previously to give small effects [15]. We have used the previous equation to evaluate the contribution of squarks to the parameter ϵ_g, for $m_A = 200$ GeV, $\tan\beta = 5, 20$, and squark masses covering the range from 200 to 700 GeV. For simplicity, we apply the 1-loop leading log formula to the Higgs masses and parameters. Results are shown in table 2, and for comparision we have also included the values obtained with universal squark masses. These results show that the effect of

non-universal masses can modify the $B.R.(h \to gg)$, by values of order $\pm 20\%$.

4.- Conclusions. We have studied the Higgs interaction with fermions and gauge bosons, and found that deviations from the SM prediction, induced by heavy quanta, can be described by a set of parameters $\epsilon_{f,V}$, which can be tested at future colliders. The production cross-section by gluon fusion can be used to probe ϵ_g at Tevatron, whereas the promising Higgs decays into WW^* can probe ϵ_W. We find that the resulting bounds may imply the exclusion of heavy particles that receive their mass directly from the SM Higgs, including a 4th standard or mirror family or chiral colored sextets and octets. For the 4th family case we disply a relations between $\epsilon_{f,V}$ and the Peskin-Takeuchi parameter T. Within the MSSM, we also find that gluon fusion is a sensitive probe for a non-universal spectrum of squarks masses, which allows for the possibility to test the sfermion masses predicted in the models of SUSY breaking. Whether the discovery of a Higgs signal will lead Particle Physics into a dark middle-age or into a renaissance remains to be seen, but the answer will depend crucially on our hability to meassure the Higgs properties, which could reveal us the path to the promised land of new physics or may be just the boring solitude of the SM up to very heavy scales.

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FIGURE CAPTION

Fig 1. 95 % exclusion contours for the parameter ϵ_g that can be obtained from Higgs search at Tevatron RUN-II, with 2 (dashes) and 10 (solid) fb^{-1} of integrated luminosity. The straight (dashed) lines corresponds to $\epsilon_g = 2$.

TABLE CAPTION

Table 1. Upper limits to 4th generation fermion masses that can be obtained from Higgs search at Tevatron RUN-II, with 10 fb^{-1}.

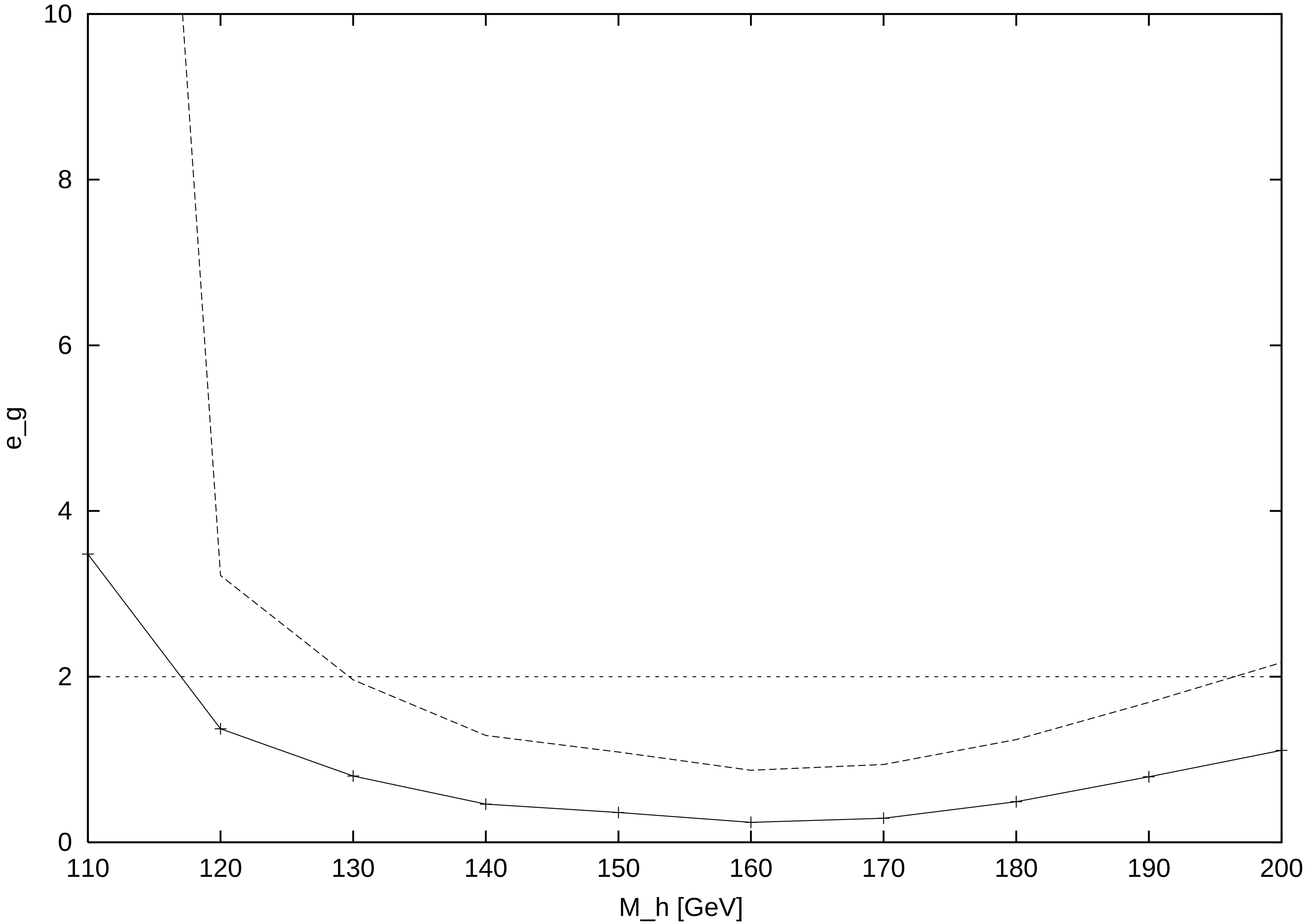
Table 2. Values predicted for the parameter ϵ_g for the MSSM with $\tan\beta = 5, 20$. $M_{\tilde{Q}}$ represents the range of values taken for $M_{\tilde{U}_R}$, $M_{\tilde{D}_L}$, $M_{\tilde{D}_R}$.

Table. 1

m_h [GeV]	m_{4th}^{max} [GeV]
120.	350.
130.	520.
140.	650.
150.	730.
160.	870.
170.	710.
180.	670.
190.	600.
200.	510.

Table. 2

$m_{\tilde{U}}$ [GeV]	$m_{\tilde{Q}}$ [GeV]	ϵ_g (non-univ)	ϵ_g (univ)
200.	$200 \to 700$	$0.1 \to 0.4$	0.4
500.	$200 \to 700$	$-0.05 \to 0.14$	0.05
700.	$200 \to 700$	$-0.05 \to 0.18$	0.1


10
8
6
4
2
0
e_g
110
120
130
140
150
160
170
180
190
200
M_h [GeV]